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14. ABSTRACT

Using commercially available components at a cost comparable to conventional free-space optics, we have built a miniaturized version of the optical setup for an atomic fountain that fits onto a 40 cm by 55 cm rack-mounted breadboard. With this system, light from an input fiber is split into ten fiber-coupled output beams: two frequency-tunable sets of three collection/launching beams, beams for repumping and detection, and two diagnostic beams. The output fibers deliver the laser light to integrated optical couplers that bolt directly to the atomic-fountain vacuum chamber [1]. Approximately 30% of the light from the input fiber is available for the experiment.

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Miniaturized Atomic Fountain Optical Table

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Abstract—**Using commercially available components at a cost comparable to conventional free-space optics, we have built a miniaturized version of the optical setup for an atomic fountain that fits onto a 40 cm by 55 cm rack-mounted breadboard. With this system, light from an input fiber is split into ten fiber-coupled output beams: two frequency-tunable sets of three collection/launching beams, beams for repumping and detection, and two diagnostic beams. The output fibers deliver the laser light to integrated optical couplers that bolt directly to the atomic-fountain vacuum chamber [1]. Approximately 30% of the light from the input fiber is available for the experiment.**

I. INTRODUCTION

The construction of an atomic fountain requires a fairly complicated optical setup to generate laser light for cooling and launching atoms for high-precision microwave spectroscopy. Typically, three counter-propagating pairs of beams are used for cooling and trapping. The six beams must be frequency-tunable over many atomic line widths and intensity controlled to achieve low temperatures. A "repumper" beam is needed to transfer atoms from the lower to the upper ground hyperfine state and a resonant probe beam is used for detecting whether atoms have undergone a microwave transition. It is now standard to send this laser light to the experiment using optical fibers for robustness and spatial-mode filtering.

A setup using conventional free-space optics for splitting, frequency-shifting and stabilizing the laser output as described above can easily fill a large 2.6 m (8 ft) by 1.3 m (4 ft) optical table. This can clearly limit the versatility of an atomic fountain where space may be limited or where mobility is required. Table-sized optical setups also suffer from long optical path lengths that are sensitive to temperature change and mechanical creep, resulting in the need for frequent realignment. We have developed a compact optical system using commercially available fiber-optic and miniature free-space components that provides all of the required atomic-fountain beams and yet fits nicely into a standard equipment rack. This setup has required no realignment since its inception nine months ago.

II. OPTICAL LAYOUT

A. *High-efficiency Fiber-coupled Double Pass AOM*

To enable frequency tuning of the output beams we use acousto-optic modulators (AOMs) at 80 MHz in a double-pass "cat's eye" arrangement, as shown in Fig. 1. Laser light emitted from an optical fiber is collimated with a 2 mm focal-length aspheric lens and directed through a 5 mm polarizing beam-splitter cube (PBC). With a nominal beam diameter of 0.5 mm, we easily achieve good (~90%) diffraction efficiency on the first pass through the AOM. To provide a wide AOM tuning range and ensure good second-pass diffraction efficiency, a lens is placed between the AOM and the mirror at a distance of one focal length from each, thus forming the "cat's eye". After two passes through the quarter waveplate, the light is directed into the second arm of the PBC, where it can then be coupled into another optical fiber.

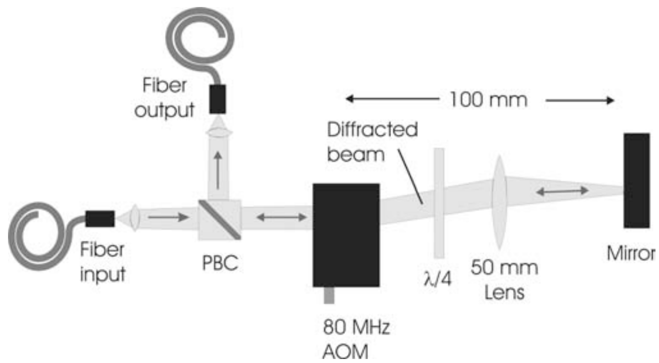

Figure 1. Diagram of the "cat's eye" double-pass arrangement used on the miniaturized optical table. Beam diameter is greatly exagerated to show lens function. In our setup, the lens and quarter waveplate are mounted together in a 25 mm diameter mount along with an iris diaphragm (not shown) that blocks the undiffracted beam.

We couple the light into an output fiber using available adjustments on the commercial fiber couplers and on the PBC mounts (see Fig. 2). Some of these adjustments rely on the restoring force from a leaf spring or a metal hinge, providing more stability than standard springs. The coupler and cube mount can be used to achieve high-precision alignment for efficient fiber coupling, providing the same

capability as the standard "dog leg" in a small fraction of the space. Because all of the fiber couplers use the same lens and have their axial position adjusted for collimation, mode matching is not much of an issue.

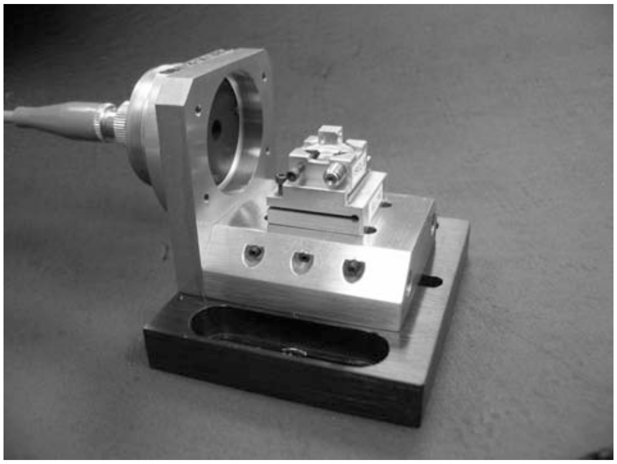

Figure 2. Fiber coupler and flexure-mounted 5 mm polarizing cube. Printed with permission of Optics For Research, Inc.[1]

Using these commercial fiber-coupling components and the "cat's eye" arrangement above, we have achieved a fiber-to-fiber coupling efficiency of up to 50%, including the double-pass AOM diffraction efficiency. The overall size of the double pass is set by the need to block the undiffracted AOM beam, which can be picked off by hand positioning an iris at a distance of 50 mm from the AOM for our 80 MHz frequency shift. This gives a footprint for the "cat's eye" double pass of approximately 200 mm by 100 mm.

B. *Optical Table Description*

A diagram of the miniaturized optical set-up is shown in Fig. 3. Laser light from a polarizing (PZ) fiber[2] is introduced onto an L-shaped table that has been machined from 20 mm thick, stainless-steel plate. Half-wave plates (not shown) and PBCs are used to split the input roughly in half and direct it toward each of two "cat's eye" double passes. The return from each double-pass is then further split into three separate beams and coupled back into output PZ fibers. The three output beams for each double-pass form the upward-directed and downward-directed beams for the collection region of the atomic fountain using a <1,1,1> launching geometry. The "L" shape was chosen to minimize the free-space propagation and to stay within the depth of field of the 0.5 mm beams. This proved to be important for achieving good coupling efficiency.

A portion of the laser light from the L-shaped table is coupled onto a separate straight table using a polarization maintaining (PM) fiber located at the elbow of the "L". On this table, a third "cat's eye" is used to produce a resonant probe beam. Repumper light is generated in the upper sideband of an electro-optic modulator (EOM) driven at 6.8 GHz by 4 W of microwave power. The fiber output at the bottom of the straight table provides diagnostic laser light for locking the laser to an FM saturated absorption spectrometer[3], and an additional fiber can be sent to a wavemeter or used as a spare output. The four AOMs used for this optical setup perform dual functions of shifting the laser frequency and providing a means to control the beam intensity by feeding back to their RF drive power. This is used to servo the laser intensities and for ramping the intensity to zero during the final moving molasses stage.

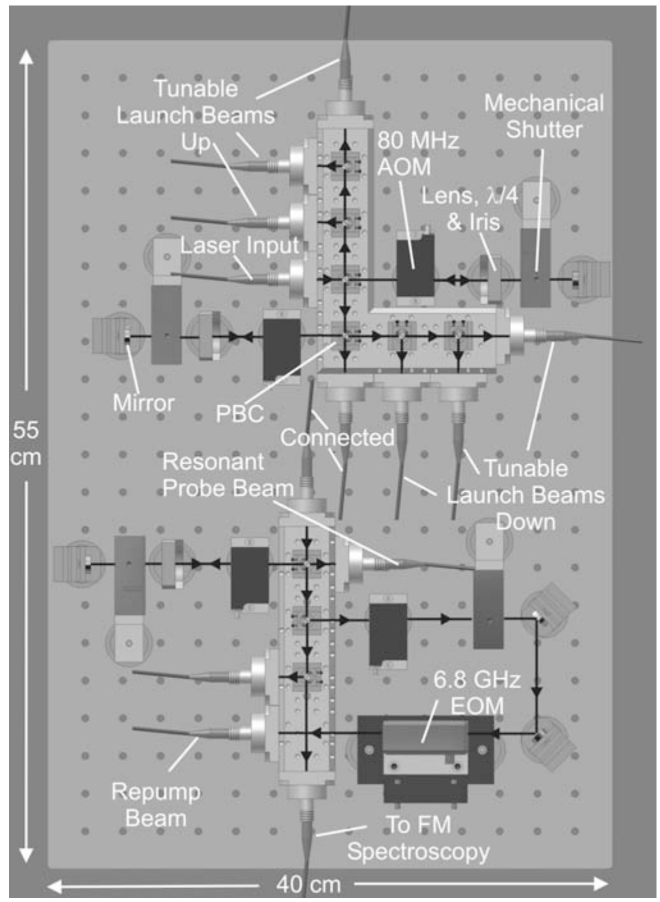

Figure 3. Diagram of miniaturized optical table used for USNO Rb atomic fountain.

Mechanical shutters are used to physically block each beam during microwave interrogation. These shutters have been mounted in a custom-built housing that can fit into the miniaturized setup. We have also made custom mounts having the proper height so that the AOMs, the lens and iris assemblies, and the flexure-style mirror mounts are rigidly

[1] The U.S. Naval Observatory does not endorse any commercial product, nor does USNO permit any use of this document for marketing or advertising.

[2] All fibers used with this table have APC polished ends, which eliminate potential problems from back reflections.

[3] In our second generation of this system, the unoccupied space on the optical breadboard is used more efficiently, allowing us to incorporate the saturated absorption setup on the same rack-mount shelf.

fixed atop 25 mm diameter stainless steel posts. The posts are then mechanically clamped to the 55 cm by 40 cm breadboard. The 5 cm thick breadboard is vibration isolation mounted on a drawer that can slide in and out of the equipment rack for access and is entirely enclosed in plexiglass to repel dust and wayward fingers (see Fig. 4).

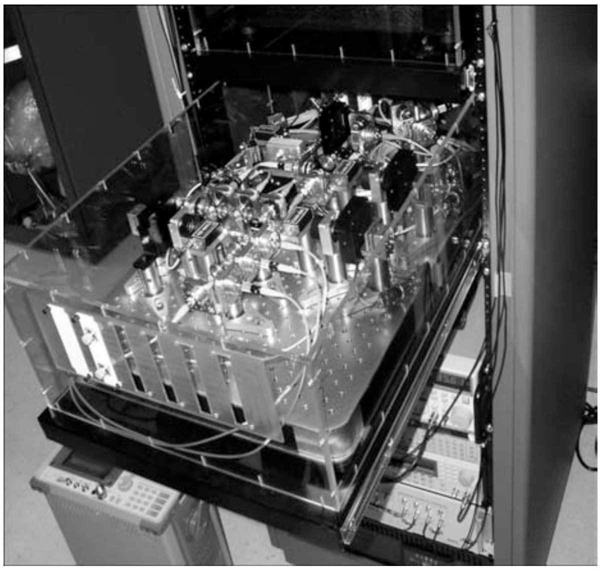

Figure 4. Picture of USNO miniaturized optical table mounted on a sliding shelf in an equipment rack.

III. PERFORMANCE

With 1 W of fiber-delivered light, the optical table provides (again via fiber) 6 cooling/launching beams with a balanced intensity of 40 mW each and delivers 45 mW to the 6.8 GHz EOM for ~2 mW of repumping light. Roughly 5 mW is split between the resonant probe beam, the FM spectroscopy output and a wavemeter output, each requiring very little input power.

For the six cooling/launching beams, this gives an average fiber-to-fiber coupling efficiency of ~30%. The drop from 50% is due to the increased difficulty in coupling the output of the "cat's eye" double pass into three separate fibers as opposed to one and to using the AOMs for intensity stabilization. The efficiency drops again by 50% when the AOMs are detuned 15 MHz during the moving-molasses cooling stage. This did not prevent us from attaining low atom temperature (~1.5 μK) since the drop for each beam was made to be the same during the optical alignment and the intensity stabilization was switched to track the lower light level before it is ramped to zero.

The optical table has proven to maintain very stable alignment over a long period of time. It was assembled in November 2004 and has been in virtual hands free operation since January 2005 (9 months at the time of this writing). This is a significant improvement over the USNO's conventional optical set-up that can require adjustments on the order of once per month. The Rb fountain has been operated with both a Ti:Sapphire laser and a frequency-doubled telecom laser by coupling either source to the fiber input of the miniaturized optical table. No other adjustments on the optical table were necessary.

IV. CONCLUSIONS

We have constructed a miniaturized optical table that is compact, versatile and demonstrated to be useful for long-term atomic fountain operation. We will construct similar systems for the additional 5 Rb atomic fountains to be included into the USNO timescale. This optical table design would lend itself well for use in many experiments that utilize laser cooling and trapping techniques.

REFERENCES

[1] S. Peil, S.Crane, T. Swanson and C. Ekstrom, "Design and Preliminary Characterization of the USNO Rubidium Fountain," Proceedings of the IEEE International Frequency Control Symposium, 2005.